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13. ABSTRACT (Maximum 200 words)

The present report contains the results of a three-year study conducted at Lehigh University into electrorheological (ER) material based smart structures. The program completed at Lehigh involved closely related and fully coupled investigations into ER smart stuctures testing and modeling, fiber-optic based in-situ structural vibration monitoring, and real-time neural network based vibration control. In order to facilitate the basic science advancements realized, five structural beam-like and plate-like configurations were focused on throughout the project. For each of these configurations, a structural vibration model was developed and tested with corresponding experimentation. Novel fiber-optic sensors and neural network controllers were also developed, and in several cases these were implemented into ER based smart structure experiments to yield physical demonstrations of fully smart or adaptive structures. It was concluded that the concept of ER smart structures for Army applications remains promising and that the models developed can now be used to evaluate that promise. The development of improved and stronger ER materials in the future, however, is likely to required for many proposed applications of the technology.

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FINAL PROGRESS REPORT

ARO PROPOSAL NUMBER: 30874-EG-SM

PROJECT PERIOD: 1 October 1992 - 31 December 1995

TITLE OF PROPOSAL: Electrorheological Material Based Smart Structures

CONTRACT OR GRANT NUMBER: DAAL03-92-G-0388

NAME OF INSTITUTION: Lehigh University

AUTHORS OF REPORT: John P. Coulter
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STATEMENT OF THE PROBLEM STUDIED:

Project Objective:

The interdisciplinary research program that was completed focused on the advancement of the science base related to ER material based smart structures in directions most appropriate to U.S. defense needs. Distributed structure vibration and acoustic control applications were considered. **The overall goal of the program was to realize the first time demonstration of completely understood and optimally designed ER material smart structures incorporating embedded vibration sensing and neural network based real-time control.** This primary program objective was approached by focusing on three interrelated secondary objectives, which were:

1. *The development of a complete understanding of the mechanical response and capabilities of ER material based controllable distributed structures.*

2. *The development and demonstration of optical fiber based embedded vibration sensing techniques appropriate for ER material based smart structures.*

3. *The development and demonstration of neural network based control approaches appropriate for ER material based smart structures.*

The integration of research components addressing each of these three secondary objectives throughout the duration of the project enabled the overall goal of the program to be realized.

Technical Approach:

An intelligent material system or smart structure can be created only through the complete integration of a controllable response capability, a sensing methodology, and a control approach. The research program conducted included components in each of these three critical areas. The specific ER smart structures research areas that were addressed are shown in Figure 1.

One component of the program focused on the understanding and design of ER material based controllable structures. This effort contained theoretical and experimental phases which directly followed from previous ER controllable structure modeling advancements. The sensing methodology component focused on optical fiber based embedded sensing approaches. Single location and distributed vibration sensing capabilities appropriate for ER material smart structures were developed and demonstrated. The controls approach was based on neural networks, and focused on both real-time ER smart structure vibration control and structural model refinement.

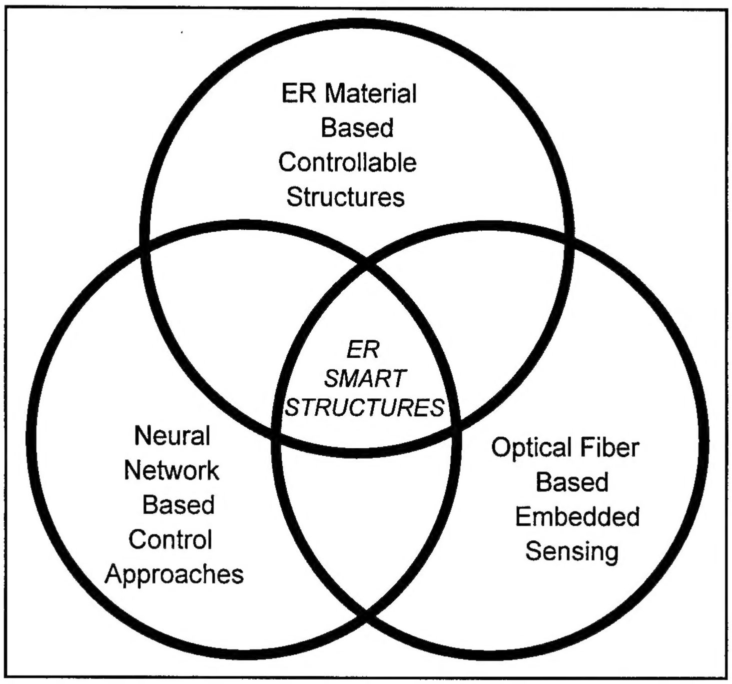

Figure 1. Cooperative interdisciplinary research approach followed during the program.

In order to facilitate the basic science advances realized during the program, five structural configuration classes were focused on. Conceptual diagramatic descriptions of the structure classes that were studied are shown in Figure 2. Structural vibration control was emphasized, and all smart structures investigated were exposed to environmental disturbances that induced lateral vibrations. All of the structural classes studied fit into what is commonly referred to as a shear configuration classification. The structures studied increased in complexity throughout the duration of the three-year program.

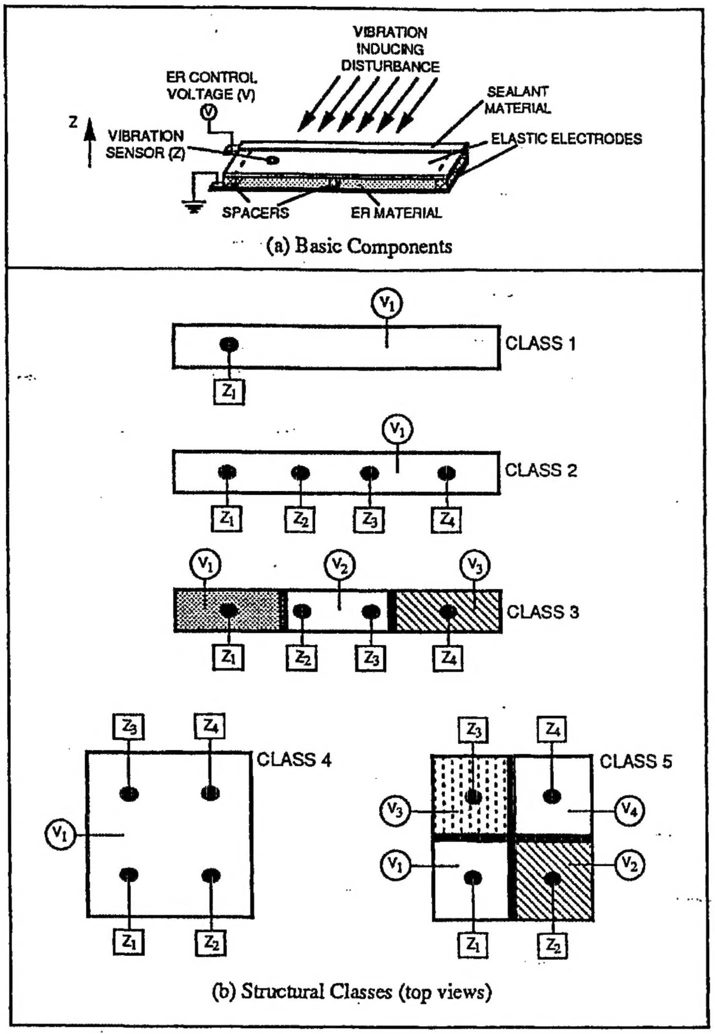

Figure 2. Structural configuration classes studied during the program.

The target structure classes were chosen to be of incrementally increasing complexity in three primary areas, which are structural dimensionality, the number and distribution of vibration sensing elements, and the number and distribution of controllable ER material based structural elements. The characteristics of each of the selected structural classes in these three areas are summarized in Table 1. Classes 1 through 3 were beam-like structures exposed to one-dimensional flexural vibration excitation environments. Class 1 structures were much like those that have been investigated previously, with one sensing location identified and one continuous ER material element that is exposed to a single controllable applied electric field. The incorporation of multiple sensing locations yielded a class 2 structure, and the further inclusion of multiple ER based control elements yielded a class 3 structure. The remaining two structure types were based on plate-like configurations exposed to two-dimensional flexural vibration environments. Class 4 structures had a distributed array of vibration monitoring elements and a single ER based control element capability. When multiple ER based control elements were added a class 5 structure was produced.

ER Smart Structure Classification	Dimensionality of Structure	Vibration Sensing Elements	ER Based Controllable Elements
1	1-D	Single-Pointwise	Single
2	1-D	Distributed: 1-D	Single
3	1-D	Distributed: 1-D	Multiple
4	2-D	Distributed: 2-D	Single
5	2-D	Distributed: 2-D	Multiple

Table 1. Primary characteristics of the Electrorheological smart structures that were studied.

SUMMARY OF THE MOST IMPORTANT RESULTS:

The development of a complete understanding of the mechanical response and capabilities of ER material based controllable distributed structures:

At the start of the project, an initial focus was placed on the evaluation of AC based electrorheological materials for smart structures applications. The AC based materials in question were newly developed by Lord Corporation, and their post-yield rheological properties (useful primarily in ER controllable devices rather than smart structures) were found to be significantly superior to those of previously developed DC based ER materials. It was therefore postulated that the AC materials would exhibit improved pre-yield response as well. Early in the project, both pure rheological and actual smart structure tests involving the AC materials were performed at Lehigh. As is common throughout the ER materials research community, the AC materials were tested at lower electric field levels due to their increased electrical current requirements. Under the conditions tested, the mechanical pre-yield response of the new AC materials was found not to be suitable for smart structures applications. ER smart structures containing the AC based material exhibited controllable damping but no significant controllable stiffness. In contrast, ER smart structures containing the more traditional DC based Lord materials exhibit significant controllability of both stiffness and damping. Contradicting this finding of superior mechanical smart structure performance with DC material, however, was the simultaneous finding that the time response of the DC materials utilized was in the case of decreasing electric field level very slow. This was realized the first time that an actual ER smart structure was tested in real-time with embedded fiber optic vibration sensing and neural network control. Unlike the millisecond ER material time response that is frequently reported on in the open literature, the actual time for a Lord DC material based smart structure undergoing small amplitude vibration to respond to a decrease in electric field was found to be as much as 30 seconds. Thus it was concluded and reported in the literature that for smart structure applications ER materials are needed which exhibit mechanical response similar to and preferably stronger than existing DC based materials and time response similar to existing AC based materials.

While the identification of the rheological challenges discussed above pose a threat to the near term implementation of ER based smart structures in actual Army defense systems, they did not cause a delay in the research directed at ER smart structures theoretical model development. During the study, the dynamic response of all five classes of ER material based homogeneous and non-homogenous adaptive beams and plate structures were investigated analytically and experimentally. An analytical model of homogeneous and non-homogenous ER adaptive beam vibrations was developed based on thin plate theory, and the transverse continuous vibration response was studied. The model was able to predict the complete structural vibration response at all locations on a structure as a function of excitation frequency and applied electric field

levels. Using similar modeling concepts applied to more dimensions, a theoretical investigation of ER adaptive plates was completed.

Simultaneous with the analytical work, all structural configurations were experimentally investigated. The non-homogeneous beams focused on experimentally were designed in a way that could allow for independent control of the electric field levels applied to four sections. Similarly, the experimental non-homogenous ER plates were designed to allow for the independent control of electric field levels applied to each of the four quadrants of the structure. ER adaptive beams and plates were fabricated and tested, and vibration responses were measured. The controllability of ER adaptive structures of these types was illustrated by emphasizing mode shape control. Variations in the mode shape amplitude and geometry were studied for various electric field configurations applied to non-homogeneous adaptive beams and plates. In all cases, the controllability of the prototype non-homogenous ER adaptive beams and plates was observed. Qualitative agreement between the theory and experiments resulted. It was concluded that the quantitative agreement could be achieved with improved ER materials and a better understanding of ER material rheology.

The development and demonstration of optical fiber based embedded vibration sensing techniques appropriate for ER material based smart structures:

The first sensor based part of project was devoted to the development of robust optical fiber sensing techniques for structural vibration. In an effort to coordinate with the modeling and neural network controller developments of the collective research investigation, polarimetric fiber optic sensors applied along the entire length of clamped-clamped ER smart beams were developed. When such a sensor was used in conjunction with a neural network controller, active control of a DC material based ER smart structure was achieved resulting in the minimization of beam vibration in the frequency range of 0-200 Hz. It should be noted that due to the slow DC material time response discussed above the structure was permitted extra time to respond when the neural network called for decreasing applied electric field adjustments.

Following this, the focus of the sensing effort turned toward pointwise rather than distributed vibration measurement. Extrinsic Fabry-Perot interferometric-type sensors were fabricated with various sensing lengths for this purpose. These sensors also exhibited preliminary sensing capabilities over a 0-200 Hz vibration frequency range, with much improved resolution and sensitivity. In addition, the Fabry-Perot sensors were found to be more robust than their polarimetric counterparts due to the fact that the sensing task is performed only along the gauge length that is actually bonded to the structure. Consequently, these sensors have greater potential for immediate application. In order to facilitate the measurement of larger strains with these sensors, an exploration of spectral modulation methods was conducted. This method obviates the need for quadrature point modulation and fringe counting. As it turned out, this led to the development of sensors capable of monitoring frequencies as high as 1000 Hz. with greater signal-to-noise (S/N) ratios than had been previously achieved. These fiber optic sensors were successfully embedded into non-homogenous ER adaptive beam structures and were able to identify the frequency of vibration accurately.

The development and demonstration of neural network based control approaches appropriate for ER material based smart structures:

The emphasis within the neural network sub-group was on the development and/or application of different types of neural network architectures to better model relationships between ER smart structure excitation frequencies, applied electric fields, and associated vibrational amplitudes at selected locations. Because the relationships identified as a result of both experimentation and theoretical modeling were found to be highly complex and nonlinear, they did not lend themselves well to traditional neural network mapping methodologies. In

addition, experiments with these traditional methodologies led to a finding that the pre specification of network architectures often results in an over or under fit of functions depending on the architecture chosen. For this reason, the Lehigh smart structures group turned its attention to a relatively unknown network type: the Dynamic Architecture Radial Basis Function (DARBF) neural network. The DARBF architecture and algorithm does not suffer many of the shortcomings of the traditional neural network methodologies. By using this method, ER smart structure mapping results were obtained that were far better than by using any other method for any of the different structural configurations studied. In one case, the fit of the function was several orders of magnitude better. On several occasions during the project period, neural network based controllers were successfully integrated with sensors embedded into into non-homogenous ER adaptive structures and real-time controllable response was realized and demonstrated.

***Technology Transfer*:**

Technology transfer during the project was accomplished mainly through publications. Four graduate students completed major thesis and dissertation works related to the project [1-4]. In addition, eight journal papers focused on structural modeling developments, vibration sensing advancements, and neural network control have appeared in *The Journal of Intelligent Material Systems and Structures*, and *Smart Materials and Structures* [5-12]. Likewise, eight papers were presented at major international conferences [13-20]. Lastly, during the project duration, Professor Coulter served on the organizing committees of a number of related conferences and as a co-editor of a major conference proceedings [21]. A detailed list of the related publications is presented as follows.

LIST OF ALL PUBLICATIONS AND TECHNICAL REPORTS:

1. Don, D. L., *An Investigation of Electrorheological Material Adaptive Structures*, Masters Thesis, Department of Mechanical Engineering and Mechanics, Lehigh University, Bethlehem, Pennsylvania, 120 pp., 1993.

2. Shiang, A. H., *A Rheological Investigation of Electrorheological Materials Subjected to Small Strains*, Masters Thesis, Department of Mechanical Engineering and Mechanics, Lehigh University, Bethlehem, Pennsylvania, 116 pp., 1994.

3. Yalcintas, M., *An Analytical and Experimentall Investigation of Electrorheological Material Based Adaptive Structures*, Doctoral Dissertation, Department of Mechanical Engineering and Mechanics, Lehigh University, Bethlehem, Pennsylvania, 369 pp., 1995.

4. Holden, D. J., *The Development of Fiber Optic Strain and Vibration Sensors for Control of Smart Structures*, Masters Thesis, Department of Mechanical Engineering and Mechanics, Lehigh University, Bethlehem, Pennsylvania, 174 pp., 1996.

5. Han. L, Voloshin, A. S., and Coulter, J. P., "Application of the Integrating Fiber Optic Sensor for Vibration Monitoring," *Journal of Smart Materials and Structures*, Volume 4, pp. 100-105, 1995.

6. Yalcintas, M., Coulter, J. P., and Don, D. L., "Structural Modeling and Optimal Control of Electrorheological Material Based Adaptive Beams," *Journal of Smart Materials and Structures*, Volume 4, pp. 207-214, 1995.

7. Yalcintas, M., and Coulter, J. P., "Analytical Modeling of Electrorheological Material Based Adaptive Beams," *Journal of Intelligent Material Systems and Structures*, Volume 6, Number 4, pp. 488-497, 1995.

8. Yalcintas, M., and Coulter, J. P., "An Adaptive Beam Model with Electrorheological Material Based Applications," *Journal of Intelligent Material Systems and Structures*, Volume 6, Number 4, pp. 498-507, 1995.

9. Yalcintas, M., and Coulter, J. P., "Electrorheological Material Based Adaptive Beams Subjected to Various Boundary Conditions," *Journal of Intelligent Material Systems and Structures*, Volume 6, Number 5, pp. 700-717, 1995.

10. Don, D. L., and Coulter, J. P., "An Analytical and Experimental Investigation of Electrorheological Material Based Adaptive Beam Structures," *Journal of Intelligent Material Systems and Structures*, Volume 6, Number 6, pp. 846-853, 1995.

11. Shiang, A. H., and Coulter, J. P., "A Comparative Study of AC and DC Electrorheological Material Based Adaptive Structures in Small Amplitude Vibration," *Journal of Intelligent Material Systems and Structures*, Volume 7, Number 4, pp. 455-469, 1996.

12. Yalcintas, M., and Coulter, J. P., "Electrorheological Material Based Non-Homogeneous Adaptive Beams," *Journal of Smart Materials and Structures*, Volume 7, pp. 128-143, 1998.

13. Coulter, J. P., Don, D. L., Yalcintas, M., and Biermann, P. J., "An Experimental Investigation of Electrorheological Material Adaptive Plates," in *Adaptive Structures and Material Systems*, G. P. Carman and E. Garcia (eds.), AD-Vol. 35, The American Society of Mechanical Engineers, New York, pp. 287-296, 1993.

14. Han, L., Voloshin, A., and Coulter, J. P., "Vibration Sensing in Electrorheological Material Controllable Structures Using Embedded Polarimetric Fiber Optic Sensors," in *Adaptive Structures and Material Systems*, G. P. Carman and E. Garcia (eds.), AD-Vol. 35, The American Society of Mechanical Engineers, New York, pp. 297-302, 1993.

15. Shiang, A. H. and Coulter, J. P., "Controllability and Reliability Issues Related to Electrorheological Material Based Adaptive Structures," in *Proceedings of the Second International Conference on Intelligent Materials*, C. A. Rogers and G. G. Wallace (eds.), Technomic Publishing Company, Inc., Lancaster, Pennsylvania, pp. 1117- 1130, 1994.

16. Yalcintas, M., and Coulter, J. P., "Analytical Modeling of Electrorheological Material Based Adaptive Beams," in *Adaptive Structures and Composite Materials: Analysis and Application,* AD-Vol. 45, MD-Vol. 54, The American Society of Mechanical Engineers, New York, pp. 101-112, 1994.

17. Flanders, S. W., Burke, L. I., and Yalcintas, M., "Alternate Neural Network Architectures for Beam Vibration Minimization," in *Adaptive Structures and Composite Materials: Analysis and Application,* AD-Vol. 45, MD-Vol. 54, The American Society of Mechanical Engineers, New York, pp. 293-298, 1994.

18. Han, L., Voloshin, A., Yalcintas, M., and Coulter, J., "Electrorheological Adaptive Structures with Embedded Sensing and Control," in *Smart Structures and Intelligent Systems*, N. W. Hagood, (ed.), Vol. 2190, The International Society for Optical Engineering, Bellingham, Washington, pp. 2-12, 1994.

19. Yalcintas, M., and Coulter, J. P., "An Adaptive Beam Model with Electrorheological Material Based Applications," in *Active Materials and Smart Structures*, G. L. Anderson and D. C. Lagoudas (eds.), Volume 2427, The International Society for Optical Engineering, Bellingham, Washington, pp. 140-162, 1995.

20. Voloshin, A., Han, L., and Coulter, J., "Vibration monitoring by a spatially integrating fiber optic sensor," in *Smart Structures and Integrated Systems*, I. Chopra (ed.), Volume 2443, The International Society for Optical Engineering, Bellingham, Washington, pp. 554-564, 1995.

21. Coulter, J. P., Brei, D. E., and Martinez, D.A., (eds.), *Adaptive Structures and Material Systems*, AD-Vol. 52, New York: The American Society of Mechanical Engineers, 816 pp., 1996.

SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED:

Students (Related Degrees Awarded):

Mr. David Don,
Department of Mechanical Engineering and Mechanics: (M.S., 1993)
Mr. Andrew Shiang,
Department of Mechanical Engineering and Mechanics: (M.S., 1994)
Ms. Melek Yalcintas,
Department of Mechanical Engineering and Mechanics: (Ph.D, 1995)
Mr. David Holden,
Department of Mechanical Engineering and Mechanics: (M.S., 1996)
Mr. Seth Flanders,
Department of Industrial Engineering
Mr. Pei-Haw Tsao,
Department of Mechanical Engineering and Mechanics

Post-Doctoral Research Associates:

Dr. Lei Han,
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Dr. Shivakumar Vaithyanathan,
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REPORT OF INVENTIONS (BY TITLE ONLY):

No invention disclosures resulted during the project period.

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